Circadian rhythms in human performance and mood under constant conditions

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SUMMARY   This study explored the relationship between circadian performance rhythms and rhythms in rectal temperature, plasma cortisol, plasma melatonin, subjective alertness and well-being. Seventeen healthy young adults were studied under 36 h of 'unmasking' conditions (constant wakeful bedrest, temporal isolation, homogenized 'meals') during which rectal temperatures were measured every minute, and plasma cortisol and plasma melatonin measured every 20 min. Hourly subjective ratings of global vigour (alertness) and affect (well-being) were obtained followed by one of two performance batteries. On odd-numbered hours performance (speed and accuracy) of serial search, verbal reasoning and manual dexterity tasks was assessed. On even-numbered hours, performance (% hits, response speed) was measured at a 25–30 min visual vigilance task. Performance of all tasks (except search accuracy) showed a significant time of day variation usually with a nocturnal trough close to the trough in rectal temperature. Performance rhythms appeared not to reliably differ with working memory load. Within subjects, predominantly positive correlations emerged between good performance and higher temperatures and better subjective alertness; predominantly negative correlations between good performance and higher plasma levels of cortisol and melatonin. Temperature and cortisol rhythms correlated with slightly more performance measures (5/7) than did melatonin rhythms (4/7). Global vigour correlated about as well with performance (5/7) as did temperature, and considerably better than global affect (1/7). In conclusion: (1) between-task heterogeneity in circadian performance rhythms appeared to be absent when the sleep/wake cycle was suspended; (2) temperature (positively), cortisol and melatonin (negatively) appeared equally good as circadian correlates of performance, and (3) subjective alertness correlated with performance rhythms as well as (but not better than) body temperature, suggesting that performance rhythms were not directly mediated by rhythms in subjective alertness.

KEYWORDS circadian, cortisol, human, melatonin, performance, rhythms, temperature

INTRODUCTION

Human beings are wilful creatures who often require the sanctions of impaired performance and increased sleepiness to drive them to bed at the appropriate time. Perhaps as a

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consequence, they feel and perform differently at one time of day to another. Such changes, which we shall denote 'psychological circadian rhythms', are assumed to be a natural by-product of the physiological circadian rhythms that are driven by the endogenous circadian pacemaker (ECP) interacting with duration of wakefulness. These rhythms serve to persuade individuals of the need to find somewhere safe to sleep at the end of their waking day, and to become active and

productive as they awake from sleep in the morning. Thus, psychological circadian rhythms fulfil something of a 'messenger role' between the ECP and the individual's conscious perceptions of biological time (Monk 1991).

Historically, the study of psychological circadian rhythms pre-dates the coinage of the terms 'circadian' and 'chronobiology' by more than half a century (see review by Lavie 1980). In the early 1900s, investigators were interested in how performance might change from one time of day to another, mostly from an educational time-tabling perspective. More recent studies of psychological circadian rhythms have developed from the traditions of Kleitman of Chicago and Colquhoun of Cambridge. Both investigators espoused a parallelism between such rhythms and the body temperature rhythm (e.g. Kleitman and Jackson 1950; Colquhoun 1971). However, later investigators from Colquhoun's group showed that for some tasks, particularly those involving short-term or working memory, there could be a breakdown in this relationship. Thus, in contrast to the evening peak in temperature, Blake (1967) showed a mid-morning peak for digit span; Folkard (1975) a mid-day peak for verbal and logical reasoning; and Folkard and Monk (1980) an early morning peak for the short term retention of prose material, replicating an original finding of Laird (1925).

Recent studies from the group of Czeisler and colleagues (e.g. Johnson *et al.* 1992) have replicated the decline in short-term memory over the waking day seen under a nycthemeral schedule (sleeping at night and awake during the day). However, when their testing was extended into a 'constant conditions' unmasking routine, with 40 h of continuous wakeful bedrest, a parallelism between performance and temperature, i.e. a coincidence in the troughs of temperature and performance, again emerged, casting doubt upon the presence of a general inversion of short-term memory and body temperature rhythms.

The body temperature rhythm has become the 'gold standard' for human circadian rhythms, much as the running wheel has for hamster studies (Wever 1979). However, one could argue that were plasma cortisol or plasma melatonin as easy to measure as body temperature, then they might, instead, be the rhythm conventionally used; there is no major conceptual or mechanistic advantage to using body temperature. The likelihood of neuroendocrine variables being successful in this regard is borne out by Patkai's (1971) study relating interindividual differences ('morningness') with daily patterns of adrenaline, and Akerstedt *et al.* (1982) study of urinary melatonin, where mean raw correlations were found of 0.45 with sleepiness ratings and −0.42 with vigilance performance over a 64 h constant conditions routine. Thus, one hypothesis to be tested by the present study was that on a circadian basis, correlations would exist between cortisol and performance and/or between melatonin and performance (perhaps in a negative direction) as exist between body temperature and performance.

Although it should also be remembered that in addition to its role as a 'marker rhythm' of the ECP, the temperature rhythm is also informing us of changes in physiological milieu that are profound, and which may themselves influence performance independently of the ECP. Thus, temperature changes may reflect changes in metabolic processes which could facilitate performance by speeding up the rate at which information is processed. The literature on this is mixed. Kleitman (1963) believed in a causal relationship between temperature and performance, and argued (Kleitman and Jackson 1950) that performance tests could be replaced by thermometers. In contrast, Colquhoun (1971) was careful to avoid this, arguing instead for a parallelism. When Rutenfranz *et al.* (1972) tried to correlate temperature changes with performance changes, holding time of day constant, they failed to find any relationship. However, when Fort *et al.* (1973) raised body temperature using baths of water, they did find a performance improvement.

In subjective alertness, there is also some evidence for a lack of parallelism with body temperature. In several studies (e.g. Monk *et al.* 1983a; Folkard and Monk 1987) alertness has been shown to exhibit a mid-day peak, contrasting with the evening peak in body temperature. However, again there is also some evidence that a parallelism might re-appear under 'constant conditions' protocols where the sleep/wake cycle is suspended (Froberg 1977; Dijk *et al.* 1992; Monk *et al.* 1992). A further hypothesis to be tested by the study thus related to how well subjective ratings (of alertness and well-being) correlate to objective performance. Were circadian rhythms in these subjective measures to be better predictors than those in the physiological indices, then this might suggest that circadian performance changes could be mediated by changes in subjective state.

To summarize, the study sought to investigate the circadian rhythms in human performance under standardized conditions of wakeful bedrest, with frequent sampling of rectal temperature and plasma cortisol and melatonin. The following three hypotheses were to be tested:

1 Circadian performance rhythms are predictable from circadian temperature rhythms, particularly for tasks with a low working memory load;

2 Significant correlations also exist between circadian performance and plasma cortisol rhythms, and between circadian performance and plasma melatonin rhythms (perhaps in a negative direction);

3 Circadian rhythms in subjective state (alertness and well-being) are better correlated with performance rhythms than are circadian physiological rhythms (temperature, cortisol, melatonin).

METHODS

Subjects

Subjects were paid volunteers aged 19–28 y (9 m, 8 f). All were carefully screened to ensure that they had a normal nycthemeral routine (mean habitual bedtime: 23:56 hours, waketime: 07:41 hours), were healthy and free of medications and drugs, and had no history of psychiatric disorders. Female subjects were studied in the early follicular phase of their menstrual cycle.

Procedure

All subjects were individually trained on the mood and performance batteries well before the start of the study. They were also given a take-home booklet containing 20 practice sessions of the mood scales, and search and reasoning tasks (described below) to be completed during the week before the actual study. Subjects entered the time isolation laboratory 24 h before the unmasking study, at which time the intravenous (i.v.) catheter and rectal probe were inserted. Approximately eight further practice sessions at each battery (see below) were given during this baseline day using identical mood and performance tests to those experienced during the 36-h unmasking routine. The night of sleep (timed to the subject's habitual routine from a 2-week sleep diary) was then recorded to ensure that a satisfactory amount of sleep was obtained prior to the unmasking routine. Following that night of sleep, the subject was allowed breakfast and a shower prior to the 36-h unmasking study (see below) that started at 09.00 hours on a Thursday morning.

Unmasking studies took place in the temporal isolation facilities of the University of Pittsburgh School of Medicine (Monk *et al.* 1992). These facilities are specially isolated from all time cues and have a constant illumination of less than 300 lux. Subjects were allowed comfortable clothing and lay on a bed, with the head tilted up by 45°. They wore standard sleep EEG electrodes (C4 referenced to $A_1 + A_2$) for monitoring wakefulness, in addition to a rectal probe for body temperature measurement and a venous catheter. Every hour the subject was offered room temperature water and a standard 'meal' comprising an amount of a liquid nutrition supplement equivalent to one 24th of the subject's daily caloric need.

Mood and performance measures

The mood and performance battery was administered using a microcomputer, with hand held 'yes' and 'no' buttons to give performance test responses, and a light pen to indicate responses to visual analogue scale (VAS) ratings. In various forms, this battery has been used routinely in the authors' laboratories since 1982, involving several thousand subject sessions. In the spirit of a heterogeneous model of circadian performance rhythms (Folkard and Monk 1985), the battery sought to provide a broad sampling of various aspects of performance. Thus, the level of cognitive complexity ranged from simple manual dexterity, through serial search to a classic working memory task (the Baddeley verbal reasoning test). Since speed and accuracy scores can show different time of day effects (Folkard 1975; Monk and Leng 1982), both were considered. These tests were all fairly short (<6 min), and some have argued that more long-term performance tests yield a more accurate picture of performance changes (Wilkinson 1970). Thus, a comparatively long (25–30 min) visual vigilance task (the Mackworth Clock Test) was also given, replacing the dexterity, search and reasoning tests on the even-numbered hours.

More complete details are given in Monk *et al.* (1985); a summary of the mood and performance battery is given below. After each hourly 'meal' of liquid food supplement and the opportunity to void, mood was assessed using eight visual analog scales (Monk 1989) which yielded global measure of vigour (alertness) and affect (well-being). On the odd-numbered hours the mood scales were followed by 32 trials of a serial search task (searching for the presence of a letter 'E' in 30 random upper case letters), 32 trials of a modified form of the Baddeley (1968) reasoning test (requiring the subject to determine whether sentences of the form 'M is not followed by $C-MC$' were true or false), and dominant and non-dominant hand versions of a dexterity task requiring the subject to fill 25 holes of a Purdue pegboard with metal pegs. Both speed and accuracy measures were recorded. After each even-numbered meal, the subject was given the mood scales as described above, followed by a 25–30 min computer visual vigilance task based upon the Mackworth Clock Test (Mackworth 1948). This comprised an image of a blank clock face, with a pointer 'clicking' around it. At an average rate of 1.5%, a 'double jump' occurred (through 12° of arc rather than 6°), to which the subject was required to respond with a button push as quickly as possible. Twenty signals occurred over a ≈ 25–30 min session. The number of 'hits' (correct detections) and the mean latency of response were recorded.

Rectal temperature

A Yellow Springs disposable thermistor was worn in the rectum to a depth of 10 cm, and was removed only for defecation. The thermistor was connected to a constant voltage generator and an ADC card in a microcomputer so that temperatures could be sampled every minute and recorded on magnetic disk and printed paper. Software detected possible slipped probes, alerting the monitoring technician. Short losses of data because of probe slippage and defecation were replaced using linear interpolation. Analyses were based on hourly averages.

Neuroendocrine rhythms

Blood sampling followed established procedures in our laboratory. Briefly, an 18-gauge i.v. catheter was inserted into a superficial forearm vein and kept patent with heparinized saline (5000 IU L^{-1}) infused at 50 mL h^{-1} then connected to a long (12 ft) catheter which in turn was connected to a three-way tap system interposed between the cannula and an i.v. microdrip. This was sufficient to keep the cannula patent for at least 60 h and generally increased APTT to, at worst, 120% of control values. Samples (2 mL every 20 min) were drawn through the i.v. catheter and were centrifuged at 4°C within 1 h of collection, and the plasma stored at -30°C until assayed. Plasma melatonin concentration was measured by radioimmunoassay using antiserum obtained from J. Arendt and [³H] melatonin (New England Nuclear Corp., Boston, MA). This assay has a sensitivity of 10 pgm L^{-1}, an intraassay coefficient of variation of 10%, and an interassay coefficient of variation of 13.8%. Values reported represent the means of two

determinations for each sample. Plasma cortisol concentration was measured by radioimmunoassay, using the mean value from duplicate samples. The intraassay coefficient of variation was 6%, and interassay coefficient of variation 10–11% throughout the range of $2–25\,\mu\,dL^{-1}$. Analyses were based on hourly averages of plasma hormone concentrations.

EEG recording

Subjects wore EEG electrodes connected to a polygraph to document any inadvertent microsleeps that occurred. These data are reported elsewhere (Buysse *et al.* 1993).

Statistical analysis

The three hypotheses were tested by considering time trends across the 36 h of the vigil for the three physiological variables (rectal temperature, plasma cortisol and plasma melatonin), two mood variables (global vigour and global affect) and eight performance variables (search speed, search accuracy, reasoning speed, reasoning accuracy, vigilance hits, vigilance speed, dominant and non-dominant hand dexterity speed). One-way ANOVAs were performed to test for the main effect of time, with orthogonal polynomials subsequently testing the significance of linear, quadratic, cubic and quartic trends. Additionally, a cosinor analysis was performed whereby a single sinusoid was fitted to each subject's individual time series after removal of a linear trend (Monk and Fort 1983). Detrending took place for all variables. The cosinor analysis yielded estimates of amplitude (fitted peak minus mean level of curve), acrophase (clock time of fitted peak), and goodness of fit (percentage variance accounted for – PVA) for each subject. In addition to these individual cosinor analyses, cosinor fits to the group mean data were used to derive a more precise estimate of rhythm timing for reporting purposes.

Analysis of the correlation between different circadian rhythms proceeded as follows: For each of the eight performance variables, each subject gave 18 time points (vigilance on the even hours, other performance measures on the odd) over the 36 h of the experiment. Also available for each subject were 36 hourly estimates of temperature, cortisol and melatonin, and 36 hourly ratings of global vigour and global affect. Separately for each subject, each of these 13 $(8+3+2)$ time series was first detrended by expressing each datum as the deviation from a least squares regression line fitted to the time series. For the sake of uniformity, this detrending process was applied to all time series (although for temperature and melatonin there was no reliable linear trend – see below). Then, taking the variables in pairs (e.g. temperature and search speed) a non-parametric correlation coefficient (Spearman's rho) was then calculated separately for each subject, taking 'time' as the random variable. Non-parametric correlations were used because of the radical differences in variable metrics (e.g. picograms of melatonin vs. seconds of search latency).

Considering the 17 coefficients so produced (one for each subject) a sign test was used to determine statistical reliability, testing the null that the true value of rho was zero. The mean and s.e. of rho across subjects was then calculated for each pair of rhythms for data presentation purposes (all but two of the 35 reported Spearman rho distributions were reliably Gaussian).

RESULTS

Performance measures

As revealed in Table 1, the only performance variable that failed to show a reliable time of day variation was search accuracy ($P>0.15$) which was therefore dropped from all further analyses. For the other seven performance variables the time of day effect was highly reliable ($P<0.003$ all cases), with significant (or almost significant) linear trends in all but non-dominant hand dexterity ($P>0.15$). The design of the experiment necessitated that linear trends over time confounded any residual practice ('learning curve') with declines over time as a result of fatigue as the vigil progressed. In order to concentrate upon the circadian variation, the performance data were thus de-trended prior to analysis (see above). This procedure did, of course, potentially influence the data in view of the fact that they were being applied to a non-integral number of circadian cycles (1.5). However, inspection of data using five different starting points revealed that this problem was unlikely to lead to errors of more than about 45 min in estimates of performance rhythm phase. Values of the fitted slope were influenced to a larger extent, but slope values did not figure in the present hypotheses.

Curves for (detrended) search speed (SCH SPD), verbal reasoning speed (VR SPD), and vigilance hits (VIG HIT) (correct signal detections) are plotted in Fig. 1, dexterity speed in dominant and non-dominant hands (DEX DOM, DEX NON) in Fig. 2, reasoning accuracy (VR ACC) and vigilance response speed (VIG SPD) are plotted in Fig. 3. Note that in all cases, increases on the Y axis represent better performance. Marked on the figures (with a 'V') is the time of fitted minimum from a cosinor fit to the group mean curve. Inspection of Figs 1–3 revealed considerable uniformity in the circadian performance rhythms across tasks. Most tasks showed performance troughs at around 05:00–07:00 hours. Interestingly, the least accurate verbal reasoning performance (Fig. 3) occurred at around 13:00 hours, both before and after the night of sleep loss, suggesting perhaps a 'post-lunch dip' (see Discussion).

Despite the finding that all 17 subjects showed significant ($P<0.05$) individual sinusoidal fits in temperature (and, indeed, in melatonin, and cortisol), only a relatively few subjects did so in the performance measures. At best, fewer than half (7/17) of the subjects showed statistically reliable ($P<0.05$) fits in performance, even after removal of a linear trend. Individual sinusoidal analyses involving performance rhythms were not therefore included in the present analyses.

Table 1 Results of ANOVA (*P*-values). 'Hours' factor has 18 levels for performance variables, 36 levels for mood and physiological variables (see text)

Variable†	ANOVA hours +	Orthogonal polynomials				
		1	*2*	*3*	*4*	*5*
Performance						
Search speed	0.0049*	0.0330*	n.s.	0.0391*	n.s.	0.0742
Search accuracy	0.2036	n.s.	n.s.	0.0416*	n.s.	n.s.
Reasoning speed	0.0001*	0.0025*	n.s.	0.0001*	0.1777	0.0625
Reasoning accuracy	0.0395*	0.0825	n.s.	0.1063	0.0191*	n.s.
Vigilance speed	0.0000*	0.0001*	0.1466	0.0121*	0.0983	0.0633
Vigilance hits	0.0000*	0.0000*	0.0356*	0.0000*	n.s.	0.0001*
Dominant hand speed	0.0000*	0.0529	0.0080*	0.0577	0.0532	0.0061*
Non-dominant hand speed	0.0000*	0.1861	0.0238*	0.0014*	0.1098	0.0297*
Mood						
Vigour	0.0000*	0.0000*	0.0000*	0.0004*	0.0046*	0.0810
Affect	0.0015*	0.0039*	0.0190*	n.s.	0.0181*	n.s.
Physiological						
Temperature	0.0000*	n.s.	0.0000*	0.0001*	0.0000*	0.0015*
Melatonin	0.0000*	n.s.	0.0000*	0.0584	0.0000*	n.s.
Cortisol	0.0000*	0.0105*	n.s.	0.0000*	n.s.	0.0000*

* Significant at 0.05; n.s. denotes *P*>0.20; † *n*=17, but reduced occasionally by equipment failure; + after Huynh-Feldt correction.

Physiological measures

The temporal variation in rectal temperature, plasma cortisol and plasma melatonin are illustrated in Fig. 4. Again, the time of cosinor minimum is marked with a 'V' on the figure, and reported in parentheses in the text. These average curves showed normal patterns with a trough in temperature at 05:00 hours, a cortisol peak at 07:00 hours and a melatonin onset at 21:00 hours. Analysis of variance confirmed the significance of the time of day variation (*P*<0.0001 all cases), with significant higher order (2–5) polynomials in most measures, but a significant linear effect only appearing in cortisol. Further details are given in Table 1. Sinusoidal fits were statistically significant in all 17 subjects for all three measures: Mean individual acrophases were at 16:41 hours (temperature), 08:45 hours (cortisol) and 02:39 hours (melatonin); mean values for all the fitted parameters are given in Table 2. Sinusoidal fits accounted for an average of more than 50% of the variance, even for melatonin and cortisol whose rhythms are not sinusoidal in shape.

Correlations between physiology and performance

Following the de-trending procedure (see above), correlations were made between the seven performance curves and the three physiological curves (rectal temperature, plasma cortisol, and plasma melatonin) separately for each subject, and the mean correlations then displayed (Fig. 5). Better performance was generally associated with higher levels of body temperature and with lower levels of cortisol and melatonin. Of the seven performance variables, vigilance speed and hits, and non-dominant hand dexterity speed were reliably correlated with all three physiological rhythms, verbal reasoning speed was reliably correlated with temperature and cortisol (but not melatonin), dominant hand dexterity speed with temperature and melatonin (but not cortisol) and search speed with cortisol only. Reasoning accuracy was not reliably correlated with any of the three. Examination of Fig. 5 confirms that rectal temperature performed quite well as a predictor, although for two variables (vigilance hits, reasoning speed) it was surpassed by cortisol (in a negative direction).

Hypotheses 1 was thus broadly confirmed, with body temperature correlating reliably with all performance measures except search speed and reasoning accuracy. Notably, although, while working memory processes can be invoked, perhaps, for the failure of reasoning accuracy to correlate with temperature, they cannot be invoked for search speed, which usually correlates very well with that physiological measure (Monk 1979).

Hypothesis 2 was also confirmed, with cortisol and melatonin also showing (negative) correlations with performance. Again, neither of the two plasma measures correlated with reasoning accuracy, cortisol failed also with dominant hand dexterity, and melatonin failed also with search speed and reasoning speed.

Mood and activation measures

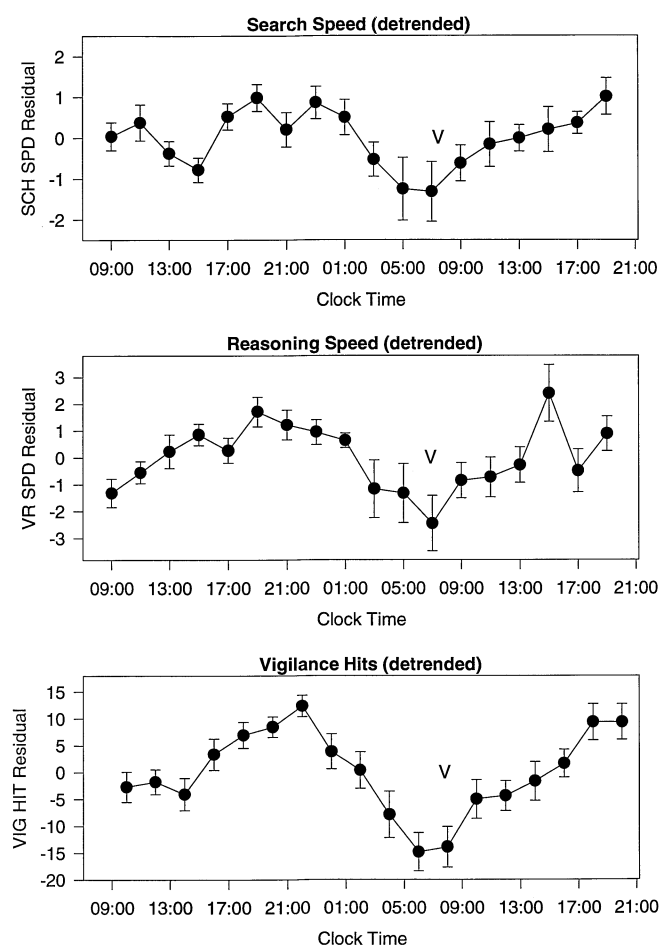Both vigour and affect showed the expected declining trend with superimposed circadian rhythmicity. When this overall

Figure 1. Performance variables. Detrended functions (see text) for SCH SPD (lines/min), VR SPD (lines/min) and VIG HIT (percentage hits). Plotted is mean ± 1 s.e.m. from 17 subjects. Fitted group mean cosinor minimum is marked V.

Figure 2. Performance variables. Detrended functions (see text) for DEX DOM and DEX NON (pegs/min). Plotted is mean ± 1 s.e.m. from 17 subjects. Fitted group mean cosinor minimum is marked V.

decline was removed by extracting a linear trend (Fig. 6), vigour (alertness) showed a trough at 06:00 hours, affect (well-being) a trough at 02:00 hours. Analysis of variance (Table 1) revealed a highly significant effect of time ($P<0.0001$ both cases), with orthogonal polynomials revealing significant linear, quadratic, cubic and quartic trends for global vigour, and significant linear, quadratic and quartic trends for global affect. Cosinor analyses revealed mean acrophases of 17:02 hours for vigour and 16:06 hours for affect (see Table 2), with 14 subjects showing statistically significant fits in vigour, 10 in affect.

Correlations between mood and performance

Correlations were made between the two (de-trended) mood curves and the seven (de-trended) performance curves, separately for each subject. The mean (± 1 s.e.m.) correlation (rho) so produced is plotted in Fig. 7. Although none of the mean correlations were very high, most were positive, with vigour (alertness) faring rather better as a predictor of performance than affect (well-being). Hypothesis 3 was definitely not confirmed for global affect which failed to
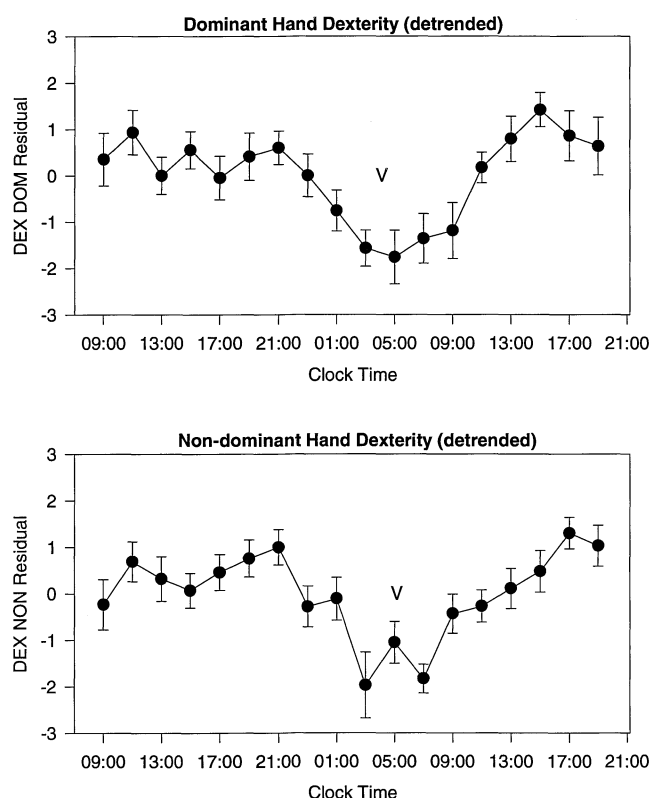
correlate with all but one of the performance variables (dominant hand dexterity speed). For global vigour, the pattern of correlations (Fig. 7) was very similar to (but not better than) that for body temperature (Fig. 5), again failing to correlate significantly in two of the seven variables. Thus, even in global vigour, there was little support for Hypothesis 3.

DISCUSSION

This study has confirmed the suggestion made by Johnson *et al.* (1992) that inter-task differences, which may result in differences in time of peak and trough under a normal nychthemeral routine, can fail to do so when the sleep/wake cycle is suspended, and endogenous circadian rhythms are 'unmasked' using a constant conditions protocol. As found by Johnson *et al.* (1992) in an immediate memory task, the present study found troughs in average performance rhythms that were mostly within the 05:00–07:00 hours time window, broadly coincident with the timing of the trough in rectal temperature. Thus, Hypothesis 1 (relating to the predictability of performance rhythms from temperature rhythms) was confirmed, even for reasoning speed – a 'working memory' task shown by Folkard (1975) to exhibit a time of day effect (under nycthemeral conditions) reliably different to that in body temperature. The only performance variable that consistently differed from temperature was, however, from that task, namely
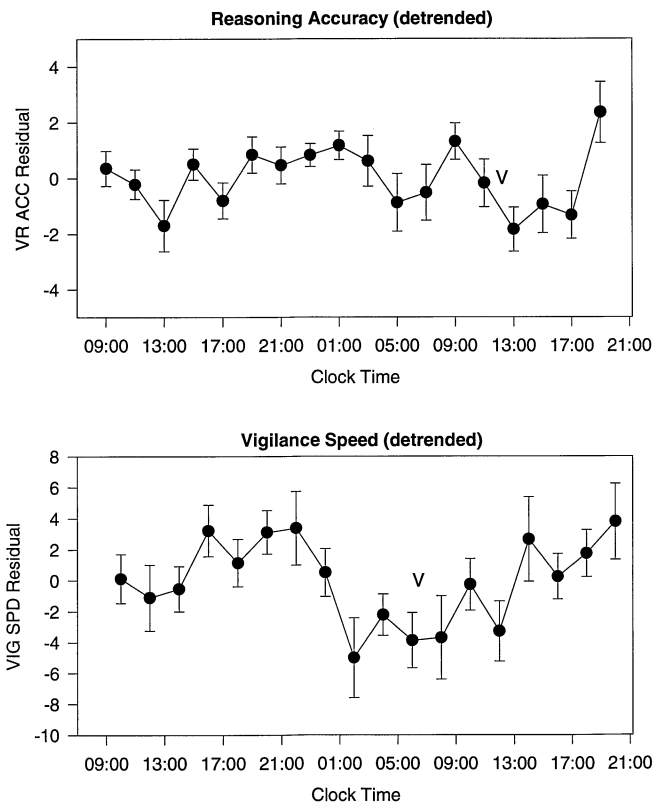
Figure 3. Performance variables. Detrended functions (see text) for VR ACC (percentage correct) and VIG SPD (button pushes/min). Plotted is mean ± 1 s.e.m. from 17 subjects. Fitted group mean cosinor minimum is marked V.

Figure 4. Physiological variables: temperature, plasma cortisol and plasma melatonin plotted as a function of hour. Plotted is mean ± 1 s.e.m. from 17 subjects. Units are °C (temperature), $\mu g\ 100\ mL^{-1}$ (cortisol) and $pg\ mL^{-1}$ (melatonin). Fitted group mean minimum is marked V.

reasoning accuracy. This variable was the weakest of the performance rhythms as indicated by the sinusoidal analysis, but did show troughs at 13:00 hours – both before and after the night of sleep loss, suggesting a bi-circadian (12 h) rhythmic component to this variable; a component, it is noteworthy, that was tracked somewhat by global vigour (Fig. 7), but not by the physiological variables (Fig. 5). This pattern does, of course, suggest a post-lunch dip (without lunch). This merits further study, since post-lunch dips are more usually seen in vigilance and perception tasks rather than in cognitive ones (Craig *et al.* 1981; Monk *et al.* 1996).

In order to understand the apparent anomaly of performance rhythms showing different patterns under nycthemeral and unmasking conditions, it is necessary to consider the various sources of circadian rhythmicity involved. As we have shown in various studies using the forced desynchronization protocol (where imposed day length [T] and free-running ECP cycles [tau] run at different periods), various mixtures of input from the endogenous circadian pacemaker (ECP) and sleep/wake cycle (SWC) combine to drive circadian rhythms in performance (Monk *et al.* 1983b) and alertness (Monk *et al.* 1989). With regard to performance, it would appear that inter-task differences under a nycthemeral routine might be driven by the additional weight given to SWC influence. Interestingly, when educed at tau (as later confirmed by Dijk *et al.* 1992), a
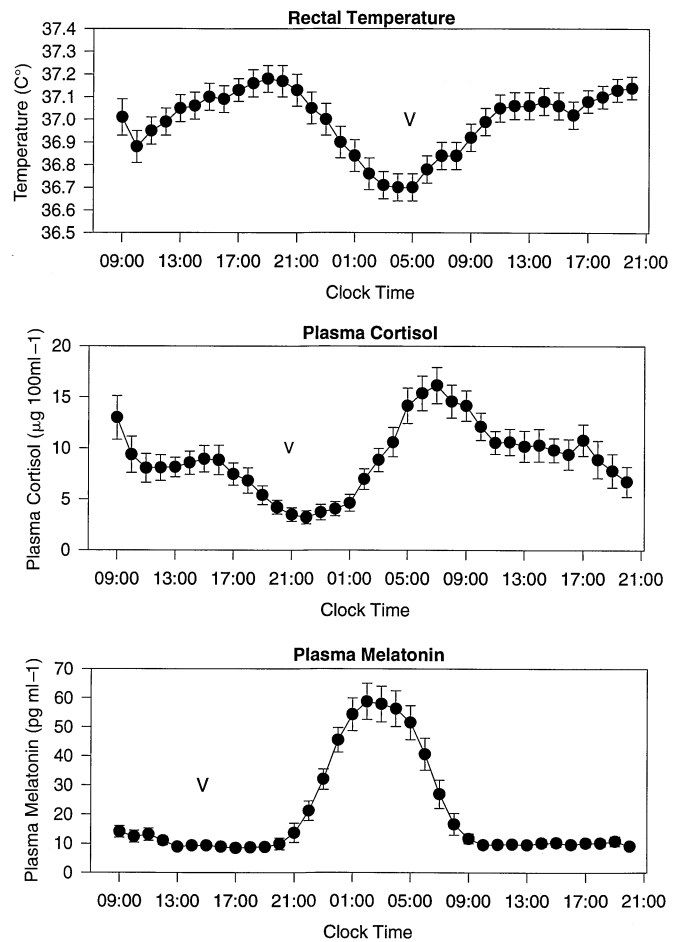
parallelism between temperature and performance occurs. This suggests the simple explanation that the parallelism observed in the present study occurs because the sleep/wake cycle has been suspended, and the linear build-up in accrued wakefulness over the vigil, akin to 'Process S' of the Borbély (1982) model, has been factored out by the removal of a linear trend. More recent work (e.g. Jewett *et al.* 1996) has suggested, however, an interaction of ECP and SWC processes, indicating a still greater complexity to the issue.

Hypothesis 2 (relating to correlations between the plasma hormone variables and performance) was also confirmed by the data. Both cortisol and melatonin showed reliable negative correlations with performance for five of the seven performance variables in cortisol and for four of the seven for melatonin. The slightly poorer predictive power of melatonin may have resulted from its relatively flat (zero) levels during most of the waking day, when performance levels were still changing.

While all three physiological rhythms were reasonably well correlated with performance, the parallelism was far from compelling, with mean correlations accounting for a rather

Table 2 Results of sinusoidal analysis on mood and physiology variables (after extraction of a linear trend). Mean and (SD) are given for all 17 subjects in all variables except acrophase, where only significant fits (*P<0.05*) are included

	Amplitude	Acrophase	Percentage variance accounted for	No. subs. sig. (P<0.05)
Vigour	9.32	17:02	33.16	14
	(3.73)	(2:18)	(14.22)	
Affect	6.22	16:06	25.66	10
	(6.72)	(4:27)	(20.98)	
Temperature	0.20	16:41	65.52	17
	(0.07)	(1:42)	(19.55)	
Cortisol	4.14	08:45	56.59	17
	(1.65)	(1:12)	(15.63)	
Melatonin	22.06	02:39	72.11	17
	(10.07)	(0:47)	(9.78)	

Units: temperature in °C, cortisol in $\mu g\,100\,mL^{-1}$, melatonin in $pg\,mL^{-1}$, vigour and affect in arbitrary units (percentage). Acrophases are in military time (hh:mm).
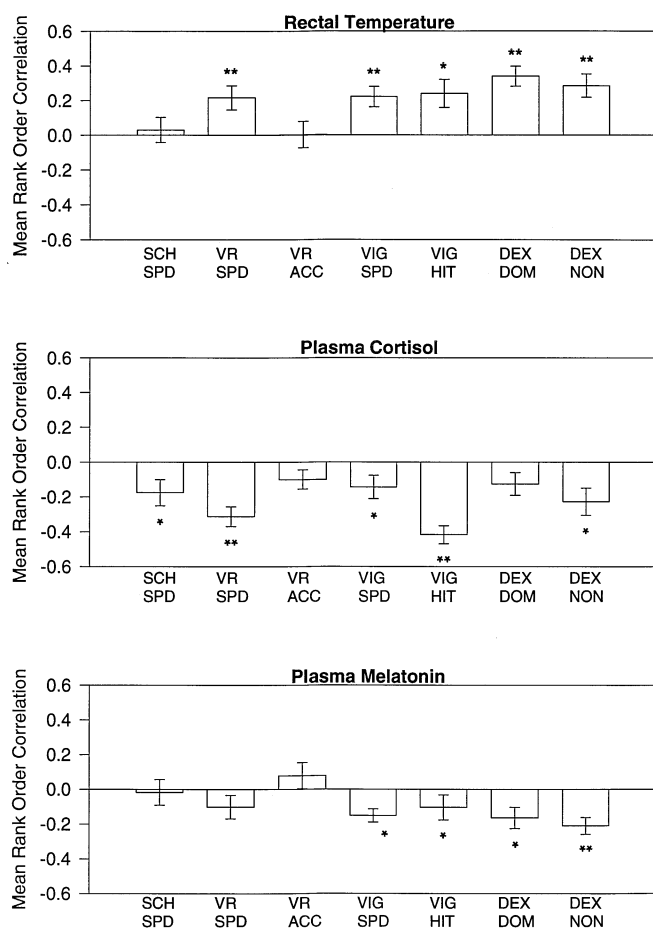

Figure 5. Mean Spearman rho correlations (± 1 s.e.m.) between physiological measures and performance measures (see text) following extraction of a linear trend. Significance: * *P<0.05*; ** *P<0.01* by sign test (*n*=17).
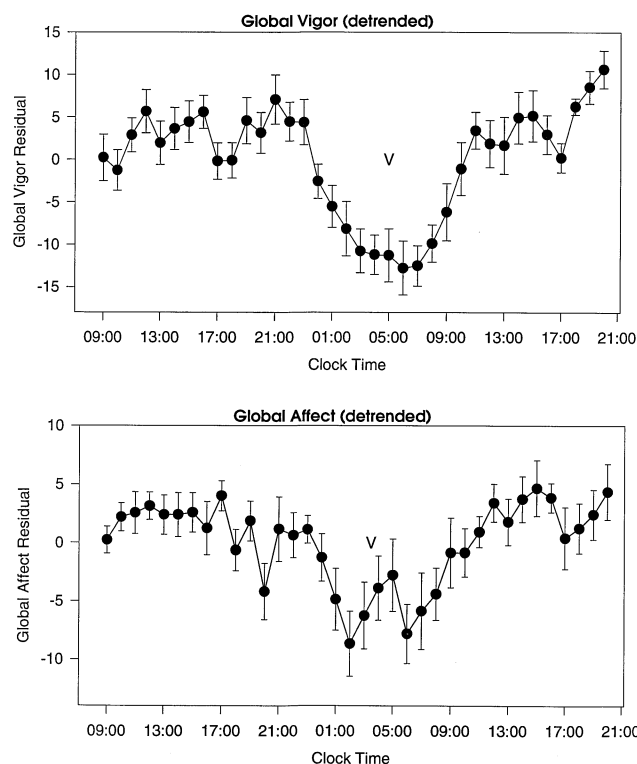

Figure 6. Mood variables: global vigour and global affect plotted as a function of hour after removal of a linear decreasing trend. Plotted is mean ± 1 s.e.m. from 17 subjects. Fitted group mean cosinor minimum is marked V.

small proportion of the variance (<10%) and a minority of subjects (2/17) showing a reverse correlation to that observed in the group as a whole even in the performance measures showing the best correlations with physiological rhythms. Thus, extreme care should be exercised in asserting, for any physiological variable, a universal parallelism between circadian rhythms in performance and physiology resulting from some causal relationship between the two. Instead, it would appear to be more parsimonious to assert that performance rhythms are driven independently by the ECP (and time since waking) with a pattern that happens to yield
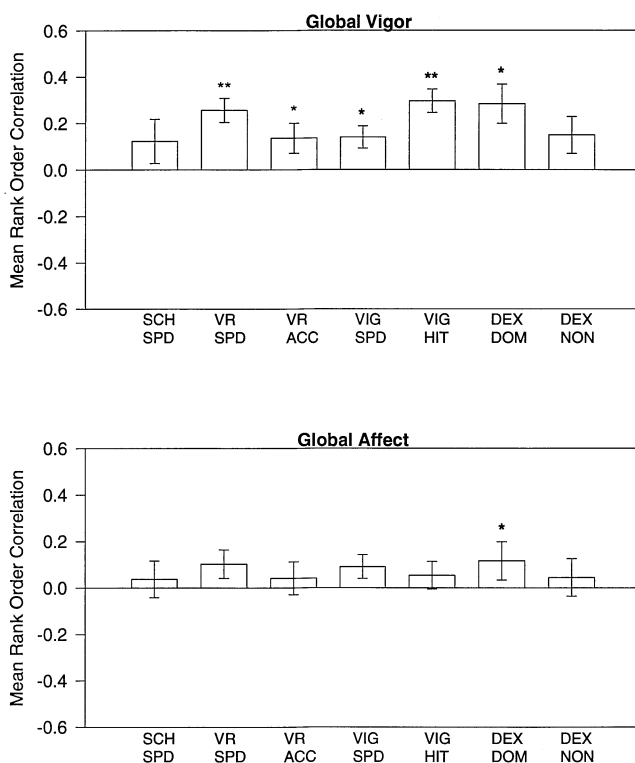
Figure 7. Mean Spearman rho correlations (± 1 s.e.m.) between mood measures and performance measures (see text) following extraction of a linear trend. Significance: * $P<0.05$; ** $P<0.01$ by sign test ($n=17$).

a positive relationship with temperature and a negative one with cortisol and melatonin, without necessarily being directly mediated by any of the three physiological rhythms.

This view is strengthened when one considers the acrophases gleaned from the sinusoidal analyses. The relative failure of performance measures to show a reliable sinusoidal pattern, in contrast to the robust sinusoids shown by all subjects in body temperature, suggests that performance rhythms are not simply a reflection of temperature changes (or, indeed, those of cortisol or melatonin which also, rather surprisingly, showed reliable sinusoidal fits in all 17 subjects). Had there truly been a parallelism with temperature, then more than seven of the 17 subjects would have shown significant sinusoidal fits in the best fitting performance measure (search speed). This failure may be partially, though, the result of non-linearity in practice and/or motivation and fatigue trends, which may have distorted the performance rhythm shape.

With regard to the subjective measures, Hypothesis 3 (that subjective ratings provide better predictive power than physiological measures) was not confirmed. Global affect (well-being) correlated very poorly with performance, achieving significance in only one of the seven variables (dominant hand dexterity speed). Global vigour (alertness) correlated with performance did as about as well as did body temperature (Figs 5 and 7) but certainly no better. The only performance variable for which it out-performed temperature was reasoning

accuracy, where it appeared to track the presence of performance dips at 13:00 hours. Generally, though, it seems unlikely that circadian changes in subjective ratings are the direct mediators of circadian performance changes.

From a different perspective, though, it should be noted that global vigour was no worse than temperature as a predictor of performance. Thus, although it may seem more rigorous to anchor performance rhythms to an objective index such as body temperature, in terms of predictability, a simple rating of alertness may work just as well.

CONCLUSIONS

Overall, the results suggest the need for extreme caution in assertions regarding the mechanism by which circadian performance rhythms occur. While undoubtedly driven by the ECP and time since waking effects, performance rhythms do not appear to be the simple direct result of circadian changes in either mood or physiology. Pathways from the ECP to cortical functions remain to be defined.

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